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Dielectric Anisotropy of Modern Microwave Substrates

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1. Introduction

The significance of the modern RF substrates in the microwave and millimeter-wave technology has two main aspects. First, there are many new materials with various dielectric characteristics, structures, compositions, sizes, specific thermal, mechanical and chemical properties and, finally, different applications. These, usually reinforced materials, containing woven or unwoven fabrics with appropriate filling, are manufactured by a variety of technological procedures and the resultant dielectric parameters (dielectric constant and dielectric loss tangent) become very informative for a reliable control of the used technology. Therefore, the manufacturers must properly characterize the parameters of their commercial products in order to control the technology and additionally, they have to keep them stable in each technological cycle. Second, the modern RF-design style is based on the utilization of powerful electromagnetic 2D/3D structure and schematic simulators, where the designed devices could be described very realistically in big details. This requirement also means that the RF designers must have accurate enough information for the actual dielectric parameters of each used material (substrate, thin film, multi-layer composite, absorber, etc.) in order to obtain an adequate simulation model of the device.

The RF designers get the needed information for the substrate parameters mainly from the manufacturer's catalogues. These data, obtained by IPC TM-650 2.5.5.5 stripline-resonator test method, include near-to-perpendicular parameters, but this is insufficient in many design cases (design of filters, hybrids, delay lines, matched elements with steps, stubs, gaps, antenna patches, etc.). Several negative facts in the design practice are very suitable to illustrate the problems. Nowadays the RF and antenna designers try to input into the simulators very detailed geometrical models of the structures of interest with extremely big details, but the values of the dielectric parameters are usually introduced rather frivolously. It is known that designers apply an ungrounded, but popular and relatively successful design technique – they usually "tune" the value of the substrate's dielectric constant about the known catalogue value in order to "fit" the simulated and the measured dependencies of a given designed device. Another surprising fact appears, when one device (passive or active) with fixed layout, manufactured on two or more substrates, produced by different manufacturers, but with equal catalogue parameters, demonstrates unequal frequency behaviour of its measured S-parameters. Similar problems appear always, when the used

reinforced substrates or the composite multi-layer materials have a noticeable dielectric anisotropy – different values of the parallel and perpendicular complex dielectric constants, and therefore – unique equivalent dielectric parameters (see section 6). Unfortunately, the dielectric anisotropy of materials is not jet an intrinsic parameter in the RF design.
In this chapter we would like to represent the increasing importance of the material's anisotropy in the modern design and the possibilities for accurate determination of this characteristic by waveguide and resonance methods. Our considerations are based mainly on the author's two-resonator method for characterization of the dielectric anisotropy (Dankov, 2006) and its subsequent variants. The main principles, backgrounds, realization and measurement problems of this method are described. Important information about the practical anisotropy of some popular substrates is presented and compared and the concept of the equivalent dielectric constant is introduced. Finally, the problem how to use the electromagnetic 3D simulators for numerical analysis of structures with anisotropic substrates is discussed and some illustrative examples are presented.

2. Characterization of the Substrate Dielectric Parameters and Possibilities to Determine the Dielectric Anisotropy

The modern reinforced PWB (Printed Wire Board) substrates have more or less expressed uniaxial anisotropy – different dielectric constants along the axes 0x, 0y and 0z. Usually, the dielectric constants in the both parallel to the substrate surface directions coincide, and the following diagonal tensor expression for the complex dielectric constant is valid:

$$\hat{\varepsilon}_r = \begin{pmatrix} \varepsilon_{||} & 0 & 0 \\ 0 & \varepsilon_{||} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix}, \text{ where } \varepsilon_{||,\perp} = \varepsilon'_{||,\perp} - j\varepsilon''_{||,\perp} = \varepsilon'_{||,\perp}\left(1 - j\tan\delta_{\varepsilon||,\perp}\right). \quad (1)$$

Thus, an anisotropy substrate can be characterized by two pairs of parameters for the dielectric constant and dielectric loss tangent: $\varepsilon'_{||}$, $\tan\delta_{\varepsilon||}$ – parallel dielectric parameters, and $\varepsilon'_{\perp}$, $\tan\delta_{\varepsilon\perp}$ – perpendicular dielectric parameters – Fig. 1*a*. The dielectric anisotropy can be expressed by two ways – as direct ratios $\alpha_{\varepsilon} = \varepsilon'_{||}/\varepsilon'_{\perp}$ and $\alpha_{\tan\delta\varepsilon} = \tan\delta_{\varepsilon||}/\tan\delta_{\varepsilon\perp}$ or as normalized ratios $\Delta A_{\varepsilon} = 2|\varepsilon'_{||} - \varepsilon'_{\perp}|/(\varepsilon'_{||} + \varepsilon'_{\perp})$ and $\Delta A_{\tan\delta\varepsilon} = 2|\tan\delta_{\varepsilon||} - \tan\delta_{\varepsilon\perp}|/(\tan\delta_{\varepsilon||} + \tan\delta_{\varepsilon\perp})$. In the last case the anisotropy can be presented in percents with positive or negative sign. The parameters α_{ε} or ΔA_{ε} represent the dielectric constant anisotropy, while the parameters $\alpha_{\tan\delta\varepsilon}$ or $\Delta A_{\tan\delta\varepsilon}$ – the dielectric loss tangent anisotropy.
Three sources of substrate anisotropy can be mentioned. The original concept for the material anisotropy is naturally connected with the magnetic or electric "gyrotropy" of some specific media (ferrites, plasmas, etc.) in external magnetic or electric fields. For example, the asymmetrical-tensor gyrotropy is an important property of the permeability of ferrite substrates or of the permittivity of semiconductor layers both in a biasing magnetic field.
The substrate gyrotropy will not be considered here. Initially the uniaxial anisotropy is connected mainly with the crystallography properties of the optical glasses, microwave ceramics (van Heuven & Vlek, 1972; Fritsch & Wolff, 1992) and liquid crystals (Gaebler et al., 2008). These materials are homogeneous, but anisotropic due to their crystalline anisotropy – different dielectric parameters along to their main crystallographic axes. Contrariwise, the source of the anisotropy of the modern artificial substrate is mainly connected with their

inhomogeneous structure of reinforcing fiber cloths, irregular filling and the miniature air "balloons" technologically inserted in the structures. We can imagine that these chaotic formations act like a great number of series or parallel capacitors depending on the electric field direction. The result is that the dielectric constant along to the glass fibers is bigger (the parallel capacitors are predominant) than the dielectric constant, perpendicular to them (the series capacitors are predominant). Usually the nonwoven substrates have less expressed anisotropy compared to woven substrates (Laverghetta, 2000). The main question is how to measure this resultant anisotropy in the whole substrates with enough accuracy?

There are a lot of measurement methods for characterization of the dielectric parameters of PWB substrates (see the useful comparison of Baker-Jarvis, 1998 and Chen et al., 2004). We will consider here only the resonance methods, because the broad-band non-resonance methods (waveguide, free-space, etc.) could not ensure the accuracy needed for determination of the anisotropy. The most spread resonance method is one of the simplest – the reference IPC TM-650 2.5.5.5 stripline-resonator method, mainly used by the substrate manufacturers – Fig. 1 *b*, *c*. The substrate under test is placed above a wide stripline conductor of length L and perturbs the resonance frequencies and the quality factors of the excited in the structure series of the resonance TEM modes. Based on simple analytical expressions this method can give near-to-perpendicular values of the dielectric constant $\varepsilon'_r \sim \varepsilon'_\perp$ and dielectric loss tangent $\tan\delta_\varepsilon \sim \tan\delta_{\varepsilon\perp}$ in a relatively big frequency range 2-15 GHz. Unfortunately, this wide spread reference method is not convenient for determination of the other pair of dielectric parameters of substrates with uniaxial anisotropy – the parallel ones, when $\varepsilon'_{||} \neq \varepsilon'_\perp$ and $\tan\delta_{\varepsilon||} \neq \tan\delta_{\varepsilon\perp}$. In fact, a modified IPC TM-650 method (by Bereskin's patent, 1992) gives an opportunity to separately determine these four parameters by "staking" of several thin unmetalized substrates into a thick bulk sample and measurements in the both directions, but this method is rather inconvenient.

The main principle to determine of the substrate dielectric anisotropy is not new – to use dual- or triple-mode resonators with predominant electric-field distribution parallel or perpendicular to the sample surface. The planar resonators (for example – the microstrip linear or ring resonators; Ivanov & Peshlov, 2002) are not accurate for anisotropy measurements, because their modes have both parallel and normal E fields in an arbitrary mixture, depending on the microstrip width. The cavity (bulk) resonators are more suitable for anisotropy measurements. Several cavity-resonator methods for low-loss dielectric property characterization have been presented in the literature. Most of them are accepted in leading metrology institutions like the National Institute of Standards and Technology (NIST), Boulder, CO, USA, and the National Physics Laboratory (NPL), Middlesex, UK for accurate reference methods for isotropic materials. However, there is no universal solution for the dielectric anisotropy characterization.

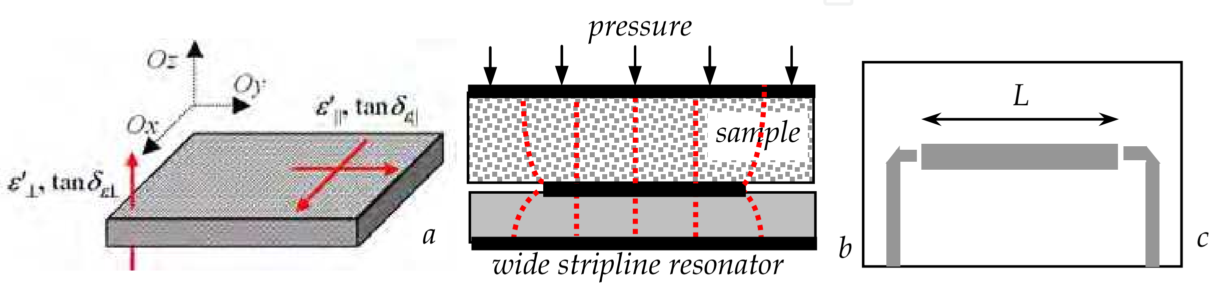

Fig. 1. Anisotropic substrate (a); IPC TM-650 2.5.5.5 test structure: side (a) and top view (b)

The parameters $\varepsilon'_{||}$ and tan$\delta_{\varepsilon||}$ can be measured simply by using popular TE-mode resonance cavities: classical Courtney's method (Courtney 1970), Kent's evanescent-mode tester (Kent 1988), NIST's mode-filtered resonator (Vanzura et al., 1993), split-cylinder resonator (Janezic & Baker-Jarvis, 1999), etc. The parameters $\varepsilon'_{\perp}$ and tan$\delta_{\varepsilon\perp}$ can be estimated using TM-mode resonance cavities (Zhao et al., 1992), low-frequency re-entrant resonators (Baker-Jarvis & Riddle 1996), etc. In fact, only a few publications have been directly dedicated to dielectric-anisotropy measurements. Whispering-gallery modes in single dielectric resonators could be used for accurate anisotropy measurement of extremely low-loss materials (Krupka et al., 1994, 1997). An early split-cavity method for the dielectric-constant anisotropy determination through a long cylindrical cavity with TE_{111} and TM_{nm0} modes is described by Olyphant, 1979, and data for some reinforced materials are presented. The number of papers dedicated to anisotropy characterization of single and multilayer materials, increases in the last several years (Tobar et al., 2001; Dankov & Ivanov, 2004; Dankov et al., 2005; Egorov et al., 2005; Dankov, 2006; Parka et al., 2007; Gaebler et al., 2008; Momcu et al., 2008, etc.). Some of them will be considered in the next sections. They are dedicated to determination of the dielectric anisotropy in a variety of materials like microwave substrates, high-K ceramics, multilayer radomes, nanocomposite layers, liquid crystals, etc. A useful summary and comparison between the existing methods for dielectric anisotropy measurements is presented by Momcu et al., 2008. Recently, simple planar resonance methods based on coplanar striplines or microstrip lines are proposed for substrate anisotropy determination in low-frequency RF substrate like FR-4 (Rautio, 2009).

3. Two-Resonator Method for Determination of the Dielectric Anisotropy

3.1 Measurement principle of the method

The basic idea for determination of the isotropic substrate dielectric parameters by an arbitrary resonance method is simple – to measure the resonance parameters (resonance frequency $f_{\varepsilon meas}$ and the unloaded quality factor $Q_{\varepsilon meas}$) of the chosen exited mode, which values are perturbed by the sample. The success of this procedure depends on the accuracy of the used model, which ensures the needed relations between the measured resonance parameters ($f_{\varepsilon meas}$, $Q_{\varepsilon meas}$) and the substrate dielectric parameters (ε'_r, tanδ_ε). The principle for determination of the uniaxial dielectric anisotropy is similar, but applied for triple- or dual-mode resonator with electric-field direction orientated strongly along to axes 0x, 0y and 0z – Fig. 1*a*. An alternative of this method is the idea to use two resonators with different modes, which support "pure" parallel or "pure" perpendicular electric field according to the surface of the sample. The main advantage is that separate resonators could be designed to suppress the parasitic modes and to simplify the measurement process.

The two-resonator method for determination of the dielectric anisotropy in multilayer materials has been proposed by Dankov & Ivanov, 2004 (see also Dankov, 2006). In its original form it is based on two different ordinary cylinder resonators, marked as R1 and R2. They support two suitable for anisotropy measurement modes – TE_{011}-mode in R1 (for determination of pure $\varepsilon'_{||}$, tan$\delta_{\varepsilon||}$) and TM_{010}-mode in R2 (for determination of pure $\varepsilon'_{\perp}$, tan$\delta_{\varepsilon\perp}$) – see Fig. 2 *a*, *b*. Each resonator is a cylinder with diameter $D_{1,2}$ and height $H_{1,2}$. A unmetalized disk sample with diameter $D_s = D_1$ or $D_S = D_2$, manufactured from the substrate by cutting with special punch, is placed in the middle of the resonator R1 or on the bottom side of the resonator R2.

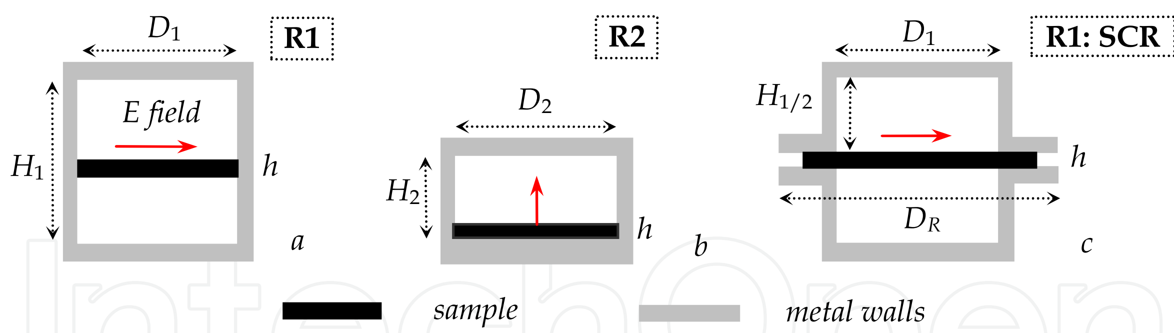

Fig. 2. Ordinary pair of cylindrical resonators: *a*) TE_{011}-mode cavity **R1**; *b*) TM_{010}-mode cavity **R2**; *c*) TE_{011} split-cylinder resonator **SCR** as **R1**; E-field direction is marked by arrow

There are two possibilities to realize the two-resonator method: 1) The measuring resonators have equal diameters $D_1 = D_2$, and the measurement of $\varepsilon'_{||}$ and $\varepsilon'_{\perp}$ corresponds to different resonance frequencies denoted as $f_\varepsilon^{TE011} > f_\varepsilon^{TM010}$. This case is more suitable for materials with a relatively weak frequency dependence on the dielectric constant and loss tangent; 2) The resonators have diameters $D_1 > D_2$,, for which the values of $\varepsilon'_{||}$ and $\varepsilon'_{\perp}$ are determined at relatively close frequencies $f_\varepsilon^{TE011} \sim f_\varepsilon^{TM010}$. One unmetalized sample is needed for the first case (the variations in the parameters from sample to sample could be avoided), while two separate samples with differing diameters have to be prepared for the second case. Thus, several pairs of resonators R1/R2 with reasonable diameters 150-15 mm could easily "cover" the frequency range 2.5-25 GHz for characterization of typical substrates with the lowest-order modes (utilization of higher-order modes will increase the upper frequency).

3.2 Measurement pairs of resonators

The measuring resonators R1 and R2 could be designed to have special features to increase their selectivity to measure the sample anisotropy. The technical details concerning the ordinary resonator pair R1/R2 are described by Dankov, 2006. The resonator R1 has two movable "contact-less" flanges with absorbing rings in order to suppress the unwanted here TM modes (compression better than –60 dB). In the same time the symmetrical TE_{011}, TE_{021}, TE_{013},… modes, suitable for determination of the longitudinal dielectric parameters, can be easily excited in transmission-power regime by two magnetic-type coaxial loops – Fig. 3. The resonator R2 has one movable flange with an improved dc contact and two magnetic-type coaxial loops with axis perpendicular to the resonator axis. A height reduction, $H_2 < (2\text{-}3)D_2$, is used to ensure single-mode excitation for determination of the transversal dielectric parameters using the lowest-order TM_{010} mode. Measurements with TM_{020}, TM_{030} modes are also possible, but the near presence of parasitic high-order modes makes the mode identification more difficult. A concrete pair of realized ordinary cylinder resonators is presented on Fig. 6*a*. The resonator dimensions are designed to be D_1 = 30.00 mm, H_1 = 29.82 mm (denoted as CR1); D_2 = 30.00 mm, H_2 = 12.12 mm (CR2′) or D_2 = 18.1 mm, H_2 = 12.09 mm (CR2). The corresponding measured resonance frequencies and unloaded Q-factors of the empty resonators are f_0^{CR1} = 13.1519 GHz, Q_0^{CR1} = 14470 in CR1 and $f_0^{CR2'}$ = 7.6385 GHz, $Q_0^{CR2'}$ = 3850 in CR2′ (or f_0^{CR2} = 12.6404 GHz, Q_0^{CR2} = 3552 in CR2). All these parameters are obtained with "daily" variations of ±0.01% in the resonance frequency and ±1.5% in the Q-factor (mainly due to room temperature changes, cavity cleanness and influence of tuning elements). We use these resonators for obtaining of the results presented in this chapter.

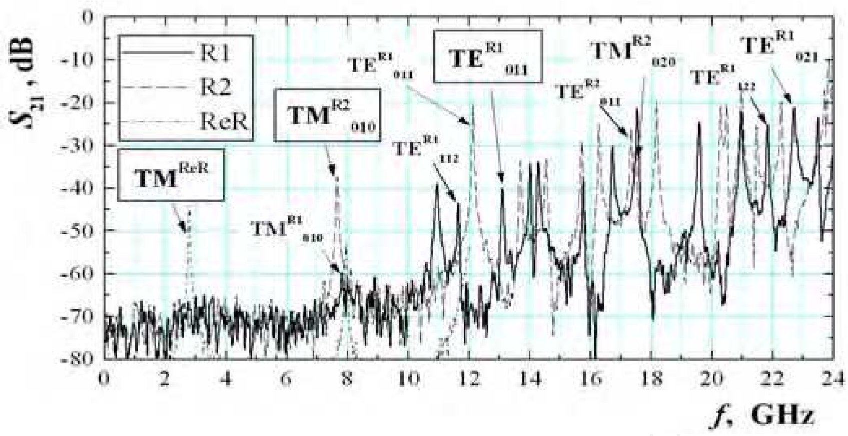

Fig. 3. Frequency responses of the R1, R2 and ReR resonators in transmitted-power regime measured by a network analyzer. The resonance curves of the discussed modes are marked

The ordinary R1 resonator can be successfully replaced with the known type of TE_{011}-mode split-cylinder resonator (SCR) (Janezic & Baker-Jarvis 1999) – see Fig. 2*c*. It consists of two equal cylindrical sections with diameter D_1 (as in CR1) and height $H_{1/2} = 0.5H_1$. The sample with thickness h and arbitrary shape is placed into the radial gap between the cylinders. If the sample has disk shape, its diameter D_S should fit the SCR diameter D_1 with at least 10% in reserve, i. e. $D_s \geq 1.1D_1$. The SCR resonator (as R1) is suitable for determination of the longitudinal dielectric parameters – $\varepsilon'_{||}$, $\tan\delta_{\varepsilon||}$. The presented in Fig. 6*a* SCR has the following dimensions: D_1 = 30.00 mm, H_1 = 30.16 mm, and the TE_{011}-mode resonance parameters – f_0^{SCR} = 13.1574 GHz, Q_0^{SCR} = 8171. In spite of the lower Q-factor, the clear advantage of SCR is the easier measurement procedure without preliminary sample cutting. The radial SCR section must have big enough diameter ($D_R \sim 1.5D_1$) in order to minimize the parasitic lateral radiation even for thicker samples (see Dankov & Hadjistamov, 2007).
The considered pair of resonators (CR1&CR2) is not enough convenient for broadband measurements of the anisotropy, even when a set of resonator pairs with different diameters is being used. More suitable for this purpose is the pair of tunable resonators, shown in Fig. 4 and Fig. 6*b*. The split-coaxial resonator SCoaxR (see Dankov & Hadjistamov, 2007) can successfully replace the ordinary fixed-size resonator R1 (or SCR), while the tunable re-entrant resonator ReR (see Hadjistamov et. al., 2007) – the fixed-size resonator R2. The SCoaxR is a variant of the split-cylinder resonator with a pair of top and bottom cylindrical metal posts with height H_r and diameter D_r into the resonator body.

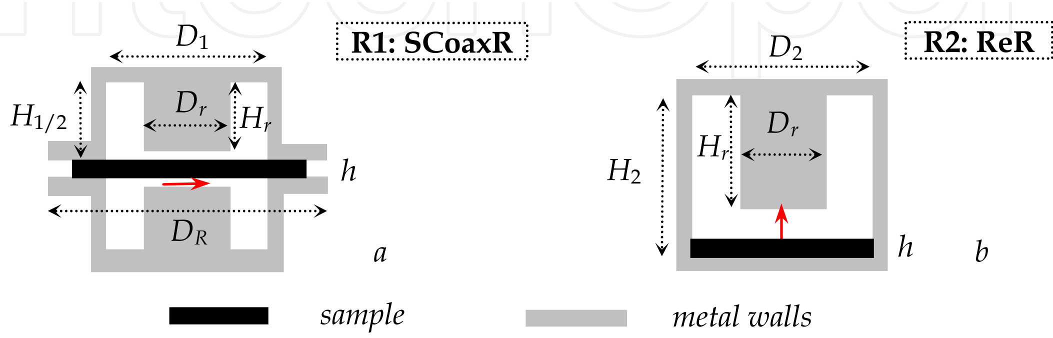

Fig. 4. Pair of tunable resonators: *a*) split-coaxial cylinder resonator **SCoaxR** as **R1**; *b*) re-entrant resonator **ReR** as **R2**

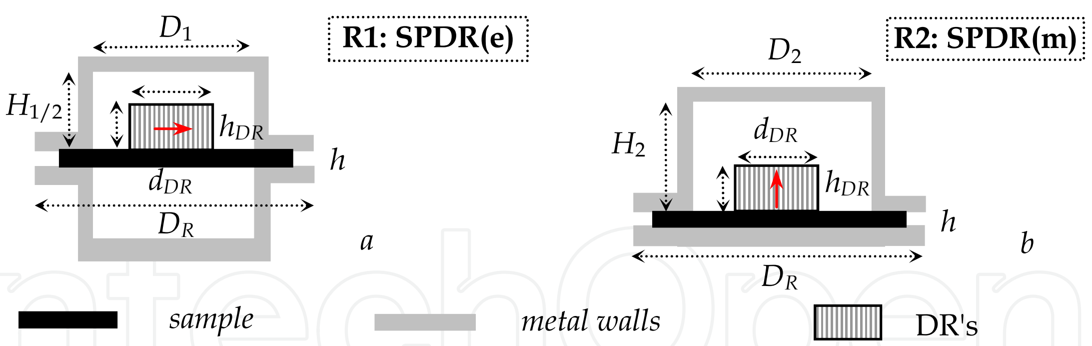

Fig. 5. Pair of split-post dielectric resonator SPDR: *a*) electrically-splitted resonator **SPDR(e)** as **R1**; *b*) magnetically-splitted resonator **SPDR(m)** as **R2**; both with one DR

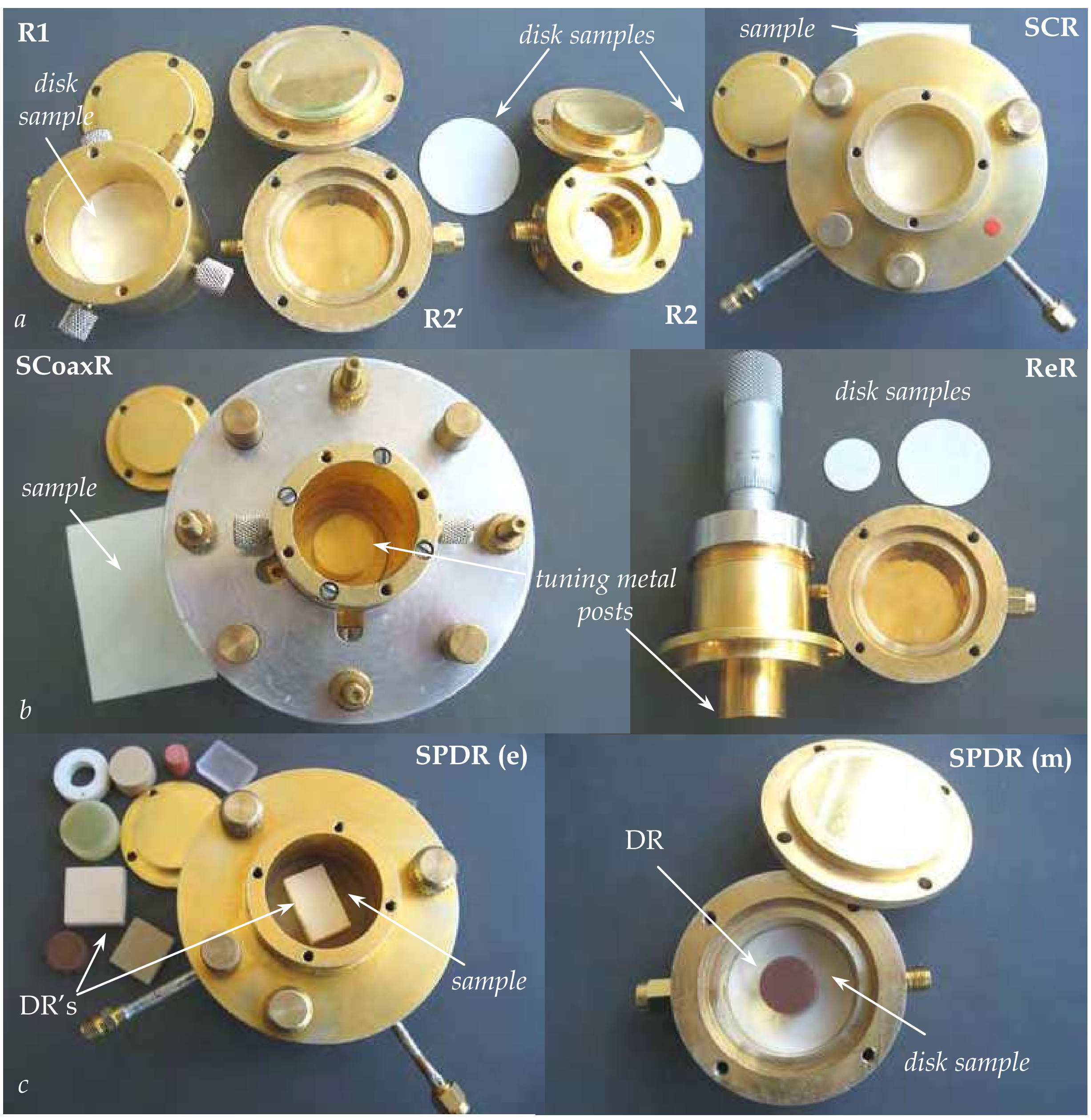

Fig. 6. Resonators' photos of different pairs: *a*) R1, R2, SCR; *b*) ReR; ScoaxR; *c*) SPDR's (e/m)

The adjustment of the resonance frequency is possible by changing of the height H_r with more than one octave below the resonance frequency of the hollow split-cylinder resonator. The re-entrant resonator is a known low-frequency measurement structure. It has also an inner metal cylinder with height H_r and diameter D_r. A problem of the reentrant and split-coaxial measurement resonators is their lower unloaded Q factors (200-1500) compared to these of the original cylinder resonators (3000-15000). In order to overcome this problem for measurements at low frequency, a new pair of measurement resonators could be used instead of R1 and R2 (see Fig. 5 and Fig. 6*c*): the split-post dielectric resonators SPDR (e/m) with electric (e) or magnetic (m) type of splitting (e.g., see Baker-Jarvis et al., 1999) (in fact, a non-split version of SPDR (m) is represented in Fig. 6*c*). The main novelty of this pair is the inserted high-Q dielectric resonators DR's that set different operating frequencies, lower than the resonance frequencies in the ordinary cylinder resonators. The used DR's should be made by high-quality materials (sapphire, alumina, quartz, etc.) and this allows achieving of unloaded Q factors about 5000-20000. A change in the frequency can be obtained by replacement of a given DR with another one. DR's with different shapes can be used: cylinder, rectangular and ring. The DR's dielectric constant should be not very high and not very different from the sample dielectric constant to ensure an acceptable accuracy.

3.3 Modeling of the measurement structures

The accuracy of the dielectric anisotropy measurements directly depends upon the applied theoretical model to the considered resonance structure. This model should ensure rigorous relations between the measured resonance parameters ($f_{\varepsilon meas}$, $Q_{\varepsilon meas}$) and the substrate dielectric parameters (ε'_r, $\tan\delta_\varepsilon$) along a given direction in dependence of the used resonance mode. The simplest model is based on the perturbation approximation (e.g. Chen et al., 2004), but acceptable results for anisotropy can be obtained only for very thin, low-K or foam materials (Ivanov & Dankov, 2002). If the resonators have simple enough geometry (e.g. CR1, CR2), relatively rigorous analytical models are possible to be constructed. Thus, accurate analytical models of the simplest pair of fixed cylindrical cavity resonators R1&R2 are presented by Dankov, 2006 especially for determination of the dielectric anisotropy of multilayer materials (measurement error less than ±2-3% for dielectric constant anisotropy, and less than ±8-10% – for the dielectric loss tangent anisotropy. The relatively strong full-wave analytical models of the split-cylinder resonator (Janezic & Baker-Jarvis, 1999) and split-post dielectric resonator (Krupka et al., 2001) are also suitable for measurement purposes, but our experience shows, that the corresponding models of the re-entrant resonator (Baker-Jarvis & Riddle, 1996) and the split-coaxial resonator are not so accurate for measurement purposes. In order to increase the measurement accuracy, we have developed the common principles for 3D modeling of resonance structures with utilization of commercial 3D electromagnetic simulators as assistance tools for anisotropy measurements (see Dankov et al., 2005, 2006; Dankov & Hadjistamov, 2007). The main principles of this type of 3D modeling especially for measurement purposes with the presented two-resonator method are described in §4. In our investigations we use Ansoft® HFSS simulator.

3.4 Measurement procedure and mode identifications

The procedure for dielectric anisotropy measurement of the prepared samples is as follows:
First of all, the resonance parameters (f_{0meas}, Q_{0meas}) of each empty resonator (without sample) from the chosen pair should be accurately measured by Vector Network Analyzer VNA.

This step is very important for determination of the so-called "equivalent parameters" of each resonator (see section 4.3); they should be introduced in the model of the resonator in order to reduce the measurement errors. Then the resonance parameters ($f_{\varepsilon meas}$, $Q_{\varepsilon meas}$) of each resonator with sample should be measured (for minimum 3-5 samples from each substrate panel). This ensures well enough reproducibility for reliable determination of the dielectric sample anisotropy with acceptable measurement errors (see section 4.4). The identification of the mode of interest in the corresponding resonator from the pair is also an important procedure. The simplest way is the preliminary simulation of the structure with sample, which parameters are taken from the catalogue. This will give the approximate position of the resonance curve. If the sample parameters are unknown, another way should be used. For example, the mechanical construction of the exciting coaxial probes in the resonators has to ensure rotating motion along the coaxial axis. Because the “pure” TE or TM modes of interest in R1/R2 resonators have electric or magnetic field, strongly orientated along one direction or in one plane (to be able to detect the sample anisotropy), a simple rotation of the coaxial semi-loop orientation allows varying of the resonance curve “height” and this will give the needed information about the excited mode type (TE or TM).

4. Measurement of Dielectric Anisotropy, Assisted by 3D Simulators

4.1 Main principles

The modern material characterization needs the utilization of powerful numerical tools for obtaining of accurate results after modeling of very sophisticated measuring structures. Such software tools can be the three-dimensional (3D) electromagnetic simulators, which demonstrate serious capabilities in the modern RF design. Considering recent publications in the area of material characterization, it is easy to establish that the 3D simulators have been successfully applied for measurement purposes, too. The possibility to use commercial frequency-domain simulators as assistant tools for accurate measurement of the substrate anisotropy by the two-resonator method has been demonstrated by Dankov et al., 2005. Then, this option is developed for the all types of considered resonators, following few principles – simplicity, accuracy and fast simulations. Illustrative 3D models for some of resonance structures, used in the two-resonator method (R1, R2 and SCR), are drawn in Fig. 7. Three main rules have been accepted to build these models for accurate and time-effective processing of the measured resonance parameters – a stylized drawing of the resonator body with equivalent diameters (D_{1e} or D_{2e}), an optimized number of line segments (N = 72-180) for construction of the cylindrical surfaces and a suitable for the operating mode splitting (1/4 or 1/8 from the whole resonator body), accompanied by appropriate boundary conditions at the cut-off planes. Although the real resonators have the necessary coupling elements, the resonator bodies can be introduced into the model as pure closed cylinders and this approach allows applying the eigen-mode solver of the modern 3D simulators (Ming et al., 2008). The utilization of the eigen-mode option for obtaining of the resonance frequency and the unloaded Q-factor (notwithstanding that the modeled resonator is not fully realistic) considerably facilitates the anisotropy measurement procedure assisted by 3D simulators, if additionally equivalent parameters have been introduced (see 4.3) and symmetrical resonator splitting (see 4.2) has been done.

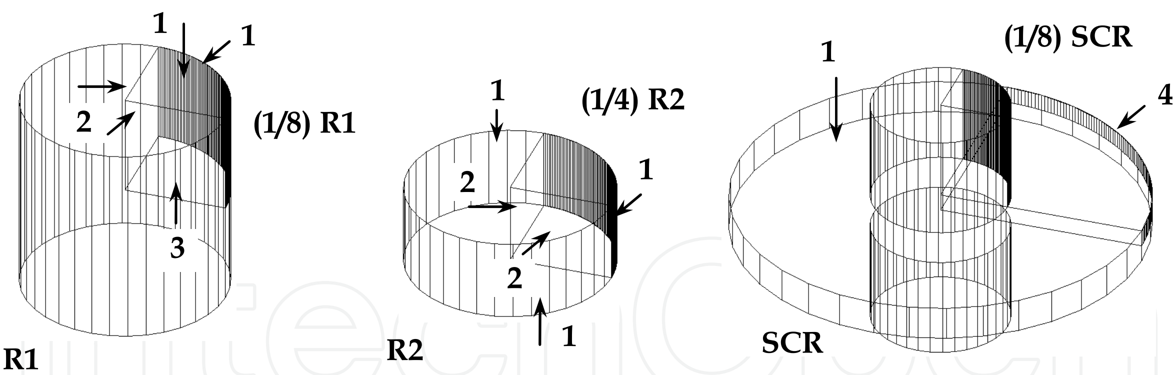

Fig. 7. Equivalent 3D models of three resonators R1, R2 and SCR and boundary conditions BC. *BC legend*: **1** – finite conductivity; **2** – E-field symmetry; **3** – H-field symmetry; **4** – perfect H-wall (natural BC between two dielectrics); the BC over the all metal surface are **1)**

4.2 Resonator splitting

In principle, the used modes in the measurement resonators for realization of the two-resonator method have simple E-field distribution (parallel or perpendicular to the sample surface). This specific circumstance allows accepting an important approach: not to simulate the whole cylindrical cavities; but only just one symmetrical part of them: 1/8 from R1, SPR and 1/4 from R2. Such approach requires suitable symmetrical boundary conditions to be chosen, illustrated in Fig. 7. Two magnetic-wall boundary conditions should be accepted at the split-resonator surfaces – "E-field symmetry" (if the E field is parallel to the surface) or "H-field symmetry" (if the E field is perpendicular to the surface). The simulated resonance parameters of the whole resonator (R1 or R2) and of its (1/8) or (1/4) equivalent practically coincide for equal conditions; the differences are close to the measurement errors for the frequency and the Q-factor (see data in Table 1). The utilization of the symmetrical cutting in the 3D models instead of the whole resonator is a key assumption for the reasonable application of the powerful 3D simulators for measurement purposes. This simple approach solves three important simulation problems: 1) it considerably decreases the computational time (up to 180 times for R1 and 50 times for R2); 2) allows increasing of the computational accuracy and 3) suppresses the possible virtual excitation of non-physical modes during the simulations in the whole resonator near to the modes of interest. The last circumstance is very important. The finite number of surface segments in the full 3D model of the cavity in combination with the finite-element mesh leads to a weak, but unavoidable structure asymmetry and a number of parasitic resonances with close frequencies and different Q-factors appear in the mode spectrum near to the symmetrical TE/TM modes of interest. These parasitic modes fully disappear in the symmetrical (1/4)-R2 and (1/8)-R1 cavity models, which makes the mode identification much easier (see the pictures in Fig. 8).

4.2 Equivalent resonator parameters

Usually, if an empty resonator has been measured and simulated with fixed dimensions, the simulated and measured resonance parameters do not fully coincide, $f_{0sim} \neq f_{0meas}$, $Q_{0sim} \neq Q_{0meas}$. There are a lot of reasons for such a result – dimensions uncertainty, influence of the coupling loops, tuning screws, eccentricity, surface cleanness and roughness, temperature variation, etc.). In order to overcome this problem and due to the preliminary decision to

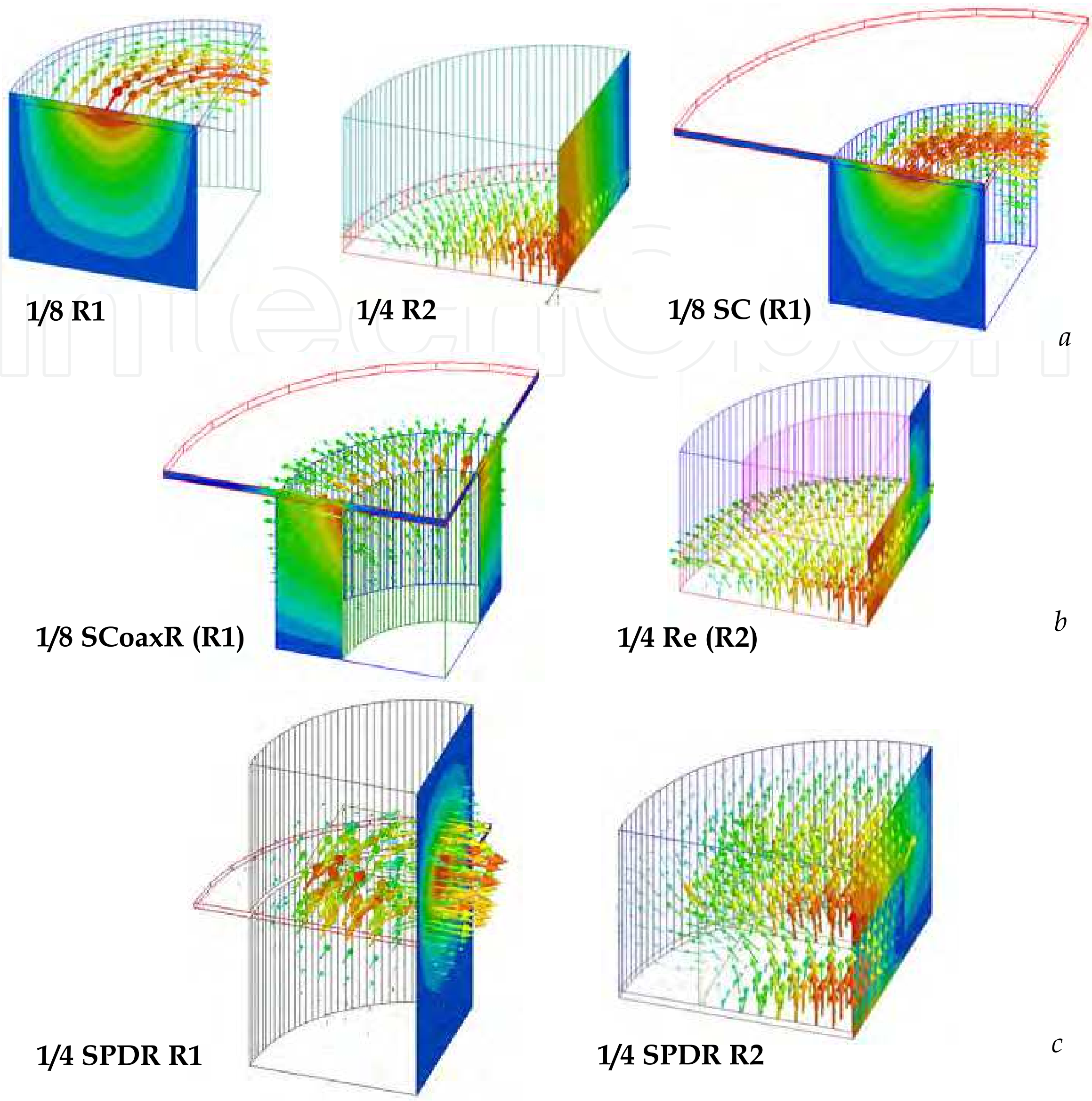

Fig. 8. Simulated electric-field E distribution (scalar and vector) in the considered pairs of measurement resonators (as R1 or R2): *a*) cylinder resonators; *b*) tunable resonators; *c*) SPDR's. Presence of similar pictures makes the mode identification mush easier.

ignore the details and to construct pure stylized resonator model, the approach, based on the introduction of *equivalent parameters* (dimensions and surface conductivity) becomes very important. The idea is clear – the values of these parameters in the model have to be tuned until a coincidence between the calculated and the measured resonance parameters is achieved: $f_{0sim} \sim f_{0meas}$, $Q_{0sim} \sim Q_{0meas}$ (~0.01-% coincidence is usually enough). The problem is how to realize this approach? Let's start with the simplest case – the equivalent 3D models of the pair CR1/CR2 (Fig. 7). In this approach each 3D model is drown as a pure cylinder with *equivalent diameter* $D_{eq1,2}$ (instead the geometrical one $D_{1,2}$), actual height $H_{1,2}$ and *equivalent wall conductivity* $\sigma_{eq1,2}$ of the empty resonators. The equivalent geometrical parameter (D instead of H) is chosen on the base of simple principle: the variation of which parameter influences most the resonance frequencies of the empty cavities CR1 and CR2?

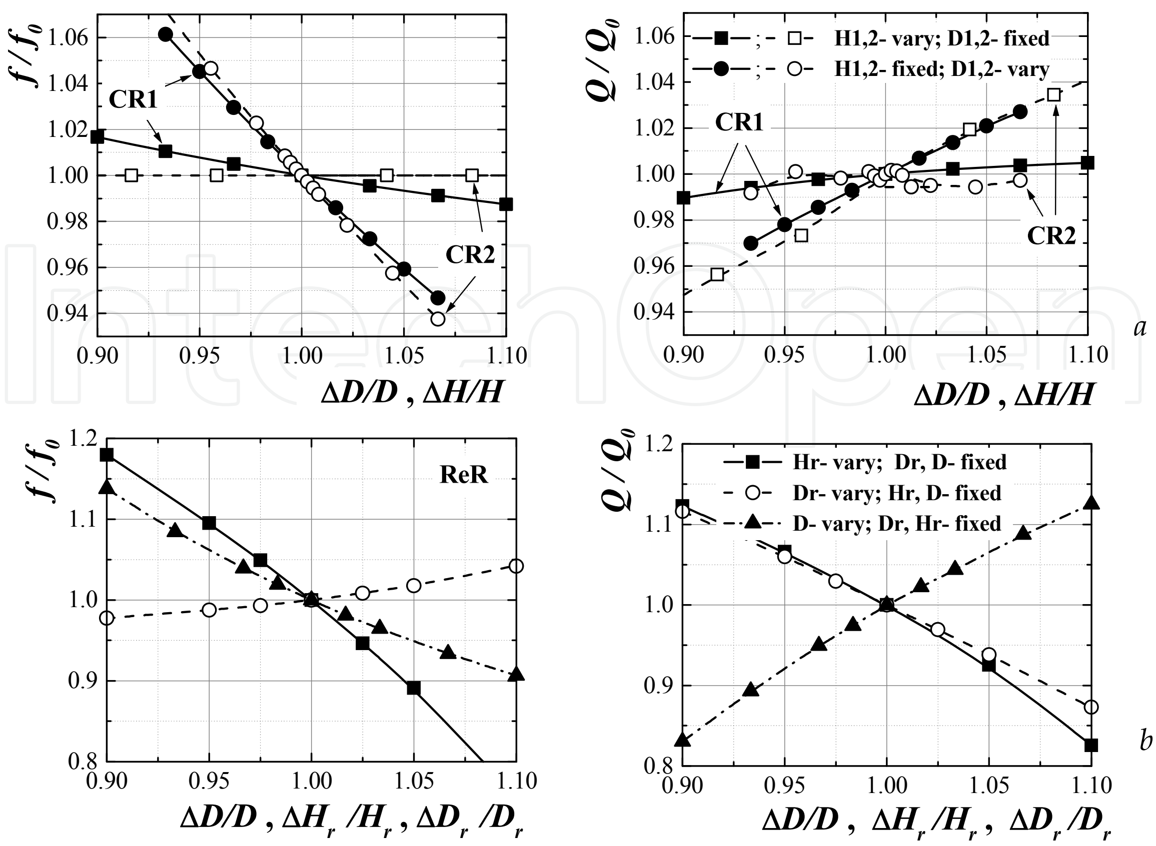

Fig. 8. Dependencies of the normalized resonance frequency and normalized Q-factor of the dominant mode in: *a*) resonators CR1/CR2; *b*) re-entrant resonator ReR, when one geometrical parameter varies, while the other ones are fixed

Resonator type	R1	(1/8) R1	R2	(1/4) R2
$f_{0\,1,2}$, GHz	13.1847	13.1846	12.6391	12.6391
$Q_{0\,1,2}$	14088	14094	3459	3462
Computational time	177 : 1		47 : 1	

Table 1. Resonance parameters of empty cavities and their equivalents (D_1 =30.0 mm; H_1 = 29.82 mm, D_2 =18.1 mm, H_2 = 12.09 mm)

N	72	108	144	180	216	288	Meas.
CR1 cavity (TE_{011} mode): D_{eq1} = 30.084 mm; σ_{eq1} = 1.70×10^7 S/m							
f_{01}, GHz	13.1578	13.1541	13.1529	13.1527	13.1523	13.1520	13.1528
Q_{01}	14086	14106	14115	14111	14108	14109	14117
CR2 cavity (TM_{010} mode): D_{eq2} = 18.156 mm; σ_{eq2} = 0.92×10^7 S/m							
f_{02}, GHz	12.6460	12.6418	12.6400	12.6392	12.6387	12.6383	12.6391
Q_{02}	3552	3475	3487	3533	3545	3571	3526

Table 2. Resonance parameters of empty cavities v/s the line-segment number *N*

The reason for this assumption is given in Fig. 8, where the dependencies of the normalized resonance frequencies and unloaded Q-factors are presented versus the relative dimension variations. We can see that the diameter variation in both of the cavities affects the resonance frequency stronger compared to the height variation. For example, in the case of CR1 or SCR the increase of D_1 leads to 378 MHz/mm decrease of the resonance frequency f_{01}, while the increase of H_1 – only 64 MHz/mm decrease of f_{01}. The effect over the Q-factor in CR1 is similar, but in the case of CR2 the Q-factor changes due to the H_2-variations are stronger. Nevertheless, we accept the diameter as an equivalent parameter $D_{eq1,2}$ for the of the cavities – see the concrete values in Table 2. We observe an increase of the equivalent diameters with 0.3% in the both cases (D_{eq1} ~ 30.084 mm; D_{eq2} = 18.156 mm), while for the equivalent conductivity the obtained values are 3-4 times smaller ($\sigma_{eq1} = 1.70\times10^7$ S/m; $\sigma_{eq2} = 0.92\times10^7$ S/m than the value of the bulk gold conductivity $\sigma_{\mathrm{Au}} = 4.1\times10^7$ S/m). Thus, the utilization of the equivalent cylindrical 3D models considerable decreases the measuring errors, especially for determination of the loss tangent. Moreover, the equivalent model takes into account the "daily" variations of the empty cavity parameters (±0.02% for $D_{eq1,2}$; ±0.6% for $\sigma_{eq1,2}$) and makes the proposed method for anisotropy measurement independent of the equipment and the simulator used.

It is important to investigate the influence of the number N of surface segments necessary for a proper approximation of the cylindrical resonator shape over the simulated resonance characteristics. The data in Table 2 show that small numbers $N < 144$ does not fit well the equivalent circle of the cylinders, while number $N > 288$ considerably increases the computational time. The optimal values are in the range $144 < N < 216$ for the both resonators CR1 and CR2. The results show that the resonator CR2 is more sensitive to the N value. The practical problem is –how to choose the right value N? We have found out that the optimal value of N and the equivalent parameters D_{eq} and σ_{eq} are closely dependent. Accurate and repeatable results are going to be achieved, if the following rule has been accepted: the values of the equivalent parameters to be chosen from the simple expressions (2, 3), and then to determine the suitable number N of surface segments in the models. The needed expressions could be deduced from the analytical models (see Dankov, 2006):

$$R_{eq1} = 182.824 H_1 \left(f_{01}^2 H_1^2 - 22468.9\right)^{1/2}, \quad R_{eq2} = 114.74274 / f_{02}, \tag{2}$$

$$\sigma_{eq1,2} = 3947.842\, f_{01,2} \big/ R_{S1,2}^2, \tag{3}$$

where the surface resistance $R_{S1,2}$ is expressed as

$$R_{S1} = 1.8798 \times 10^{-5} H_1 R_{eq1}^2 f_{01}^3 \frac{1}{Q_{01}} \left[0.5 H_1 / R_{eq1} - 1 + 2.9918 \times 10^{-5} (R_{eq1} f_{01})^2\right]^{-1}, \tag{4}$$

$$R_{S2} = 0.5 H_2 \left(2.40483 / R_{eq2}\right)^2 \frac{1}{Q_{02}} \left[5.56313 \times 10^{-5} f_{02} \left(1 + H_2 / R_{eq2}\right)\right]^{-1} \tag{5}$$

All the geometrical dimensions $R_{eq1,2}$ and $H_{1,2}$ in the expressions (2-5) are in mm, $f_{01,2}$ – in GHz, $R_{S1,2}$ – in Ohms and $\sigma_{eq1,2}$ – in S/m. After the described procedure, the optimal number N of rectangular segments in CR1/CR2 is N ~ 144-180. Similar values can be obtained by a simple rule – the line-segment width should be smaller than $\lambda/16$ (λ – wavelength). This simple rule allows choosing of the right N value directly, without preliminary calculations.

Let's now to consider the determination of the equivalent parameters in the other types of resonators. In Fig. 8*b* we demonstrate the influence of the relative shift of each of the dimensions D, D_r and H_r over the normalized resonance parameters f/f_0 and Q/Q_0 of an empty re-entrant cavity. The results show that the resonance frequency variations are strongest due to the variations of the re-entrant cylinder height H_r (±10% for $\Delta H_r/H_r$ ~ ±5%). Therefore, it should be chosen as an equivalent parameter in the 3D model of the re-entrant cavity (*equivalent height*). But the variations due to the outer diameter are also strong (±5% for $\Delta D/D$ ~ ±5%) (For build-in cylinder diameter the changes are smaller than ±1% for $\Delta D_r/D_r$ ~ ±5%). The variations of the Q-factor of the dominant mode have similar values for all of the considered parameters (note: the effects for $\Delta H_r/H_r$ and for $\Delta D/D$ have opposite signs). So, in the re-entrant cavity 3D model we can select *two equivalent geometrical parameters*: 1) equivalent outer cylinder diameter D_{eq2}, when H_r = 0 (e. g. the re-entrant resonator is a pure cylindrical resonator with TM_{010} mode) and 2) equivalent build-in cylinder height H_{eq_r}, when D_{eq2} has been already chosen. This approximation allows us a direct comparison between the results from cylindrical and re-entrant resonators, if the last one has a movable inner cylinder. Very similar behaviour has the other tunable cavity SCoaxR – we have to determine an equivalent height H_{eq_r} of the both coaxial cylinders.
The last pair of measurement resonators consists of additional unknown elements – one or two DR's. In this more complicated case, after the determination of the mentioned equivalent parameters of the empty resonance cavity (R1, SCR or R2), an "*equivalent dielectric resonator*" should be introduced. This includes the determination of the actual dielectric parameters (ε'_{DR}, $\tan\delta_{\varepsilon DR}$) of the DR with measured dimensions d_{DR} and h_{DR}. The anisotropy of the DR itself is not a problem in our model; in fact, we determine exactly the actual parameters in the corresponding case – parallel ones in SPDR (e) or perpendicular ones in SPDR(m).The actual parameters of the necessary supporting elements (rod, disk) for the DR mounting should also to be determined. The only problem is the "depolarization effect", which takes place in similar structures with relatively big normal components of the electric field at the interfaces between two dielectrics. In our 3D models the presence of depolarization effects are hidden (more or less) into the parameters of the "equivalent DR".

4.4 Measurement errors, sensitivity and selectivity

The investigation of the sources of measurement errors during the substrate-anisotropy determination by the two-resonator method is very important for its applicability. The analysis can be done with the help of the 3D equivalent model of a given structure: the value of one parameter has to be varied (e. g. sample height) keeping the values of all other parameters and thus, the particular relative variation of the permittivity and loss tangent values can be calculated. Finally, the total relative measurement error is estimated as a sum of these particular relative variations. A relatively full error analysis was done by Dankov, 2006 for ordinary resonators CR1/CR2. It was shown that the contributions of the separate parameter variations are very different, but the introduction of the equivalent parameters – equivalent $D_{eq1,2}$, equivalent height H_{eq_r} (in ReR and SCoaxR) and equivalent conductivity $\sigma_{eq1,2}$, considerably reduce the dielectric anisotropy uncertainty due to the uncertainty of the resonator parameters. Thus, the main benefit of the utilization of equivalent 3D models is that the errors for the measurement of the pairs of values ($\varepsilon'_{||}$, $\tan\delta_{\varepsilon||}$) and ($\varepsilon'_{\perp}$, $\tan\delta_{\varepsilon\perp}$) remain to depend mainly on the uncertainty $\Delta h/h$ in the sample height (Fig. 9), especially for relative thin sample, and weakly on the sample positioning uncertainty (in CR1).

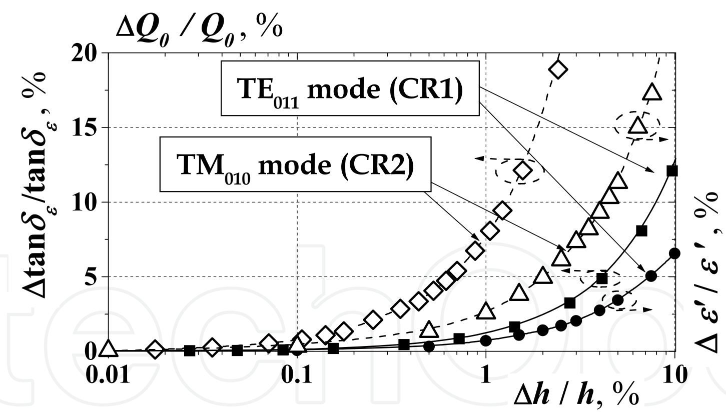

Fig. 9. Calculated relative errors in CR1/CR2: $\Delta\varepsilon'/\varepsilon'$ v/s $\Delta h/h$ and $\Delta\tan\delta_\varepsilon/\tan\delta_\varepsilon$ v/s $\Delta Q_0/Q_0$

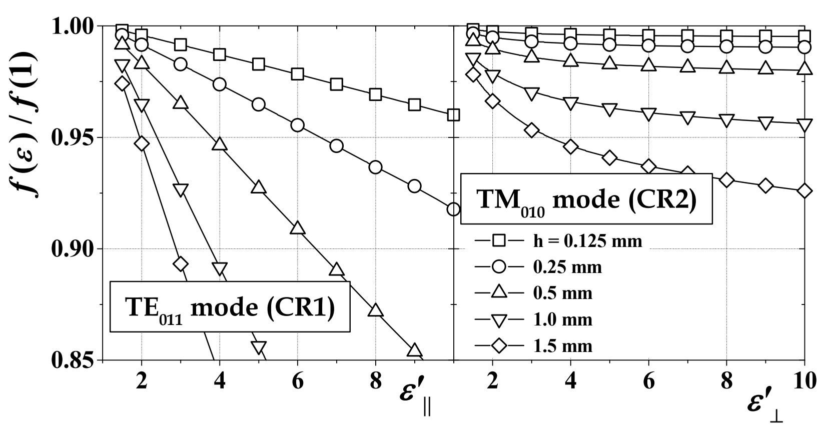

Fig. 10. Calculated sensitivity in CR1/CR2 according to sample dielectric constants $\varepsilon'_{||}$, $\varepsilon'_{\perp}$

Taking into account the above-discussed issues the measuring errors in the two-resonator method can be estimated as follows: < 1.0-1.5 % for $\varepsilon'_{||}$ and < 5 % for $\varepsilon'_{\perp}$ for a relatively thin substrate like RO3203 with thickness h = 0.254 mm measured with errors $\Delta h/h$ < 2% (this is the main source of measurement errors for the permittivity). Besides, if the positioning uncertainty reaches a value of 10 % for the sample positioning in CR1 (absolute shift up to ±1.5 mm), the relative measurement error of $\varepsilon'_{||}$ does not exceed the value of 2.5 %. The measuring errors for the determination of the dielectric loss tangent are estimated as: 5-7 % for $\tan\delta_{\varepsilon||}$, but up to 25 % for $\tan\delta_{\varepsilon\perp}$, when the measuring error for the unloaded Q-factor is 5 % (this is the main additional source for the loss-tangent errors; the other one is the dielectric constant error).

A real problem of the considered method for the determination of the dielectric constant anisotropy ΔA_ε is the *measurement sensitivity* of the TM_{010} mode in the resonator CR2 (for $\varepsilon'_{\perp}$), which is noticeably smaller compared to the sensitivity of the TE_{011} mode in CR1 (for $\varepsilon'_{||}$). We illustrate this effect in Fig. 10, where the curves of the resonance frequency shift versus the dielectric constant have been presented for one-layer samples with height h from 0.125 up to 4 mm. The shift $\Delta f/\Delta\varepsilon$ in R1 for a sample with h = 0.5 mm leads to a decrease of 480 MHz for the doubling of $\varepsilon'_{||}$ (from 2 to 4), while the corresponding shift in CR2 leads only to a decrease of 42.9 MHz for the doubling of $\varepsilon'_{\perp}$. Also, the Q-factor of the TM_{010} mode in CR2 is smaller compared to the Q-factor of the TE_{011} mode in CR1. This leads to an unequal accuracy for the determination of the loss tangent anisotropy $\Delta A_{\tan\delta\varepsilon}$, too.

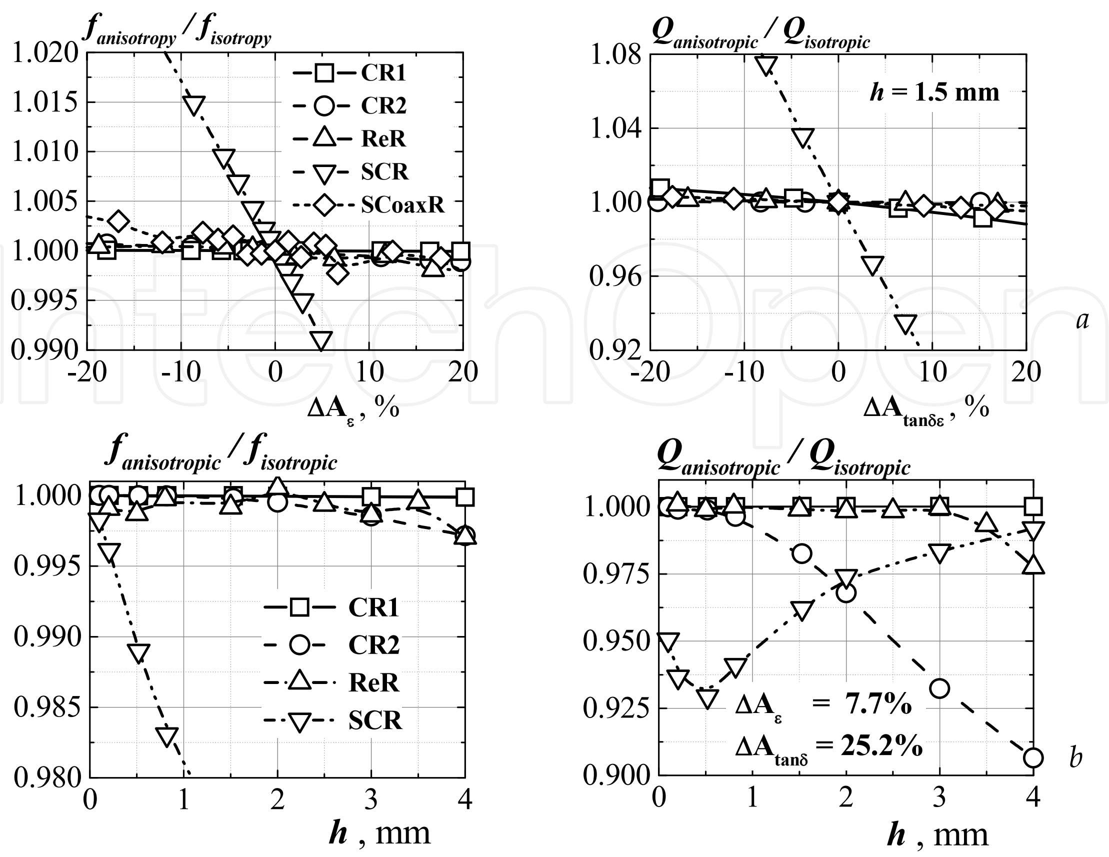

Fig. 11. Dependencies of the normalized resonance frequency and Q-factors of the resonance modes for anisotropic and isotropic samples: *a*) v/s dielectric anisotropy ΔA_{ε}, $\Delta A_{\tan\delta\varepsilon}$; *b*) v/s the substrate thickness *h*

Thus, the measured anisotropy for the dielectric constant ΔA_{ε} < 2.5-3 % and for the dielectric loss tangent $\Delta A_{\tan\delta\varepsilon}$ < 10-12 % can be associated to a *practical isotropy* of the sample ($\varepsilon'_{||} \cong \varepsilon'_{\perp}$; $\tan\delta_{\varepsilon||} \cong \tan\delta_{\varepsilon\perp}$), because these differences fall into the measurement error margins.

Finally, the problem of the *resonator selectivity* (the ability to measure either pure parallel or pure perpendicular components of the dielectric parameters) is considered. The results for the normalized dependencies of the resonance frequencies and Q-factors for anisotropic and isotropic samples in the separate resonators are presented in Fig. 11. These are two types of dependencies– according to the substrate anisotropy at a fixed thickness and according to the substrate thickness at a fixed anisotropy. How have these data been obtained? Each 3D model of the considered resonators contains sample with fixed dielectric parameters: once isotropic, then – anisotropic. The models in these two cases have been simulated and the obtained resonance frequencies and Q-factors are compared – as ratio $(f, Q)_{anisotropic} / (f, Q)_{isotropic}$. The presented results unambiguously show that most of the used resonators measure the corresponding "pure" parameters with errors less than ±0.3-0.4 % for dielectric constant and less than ±0.5-1.0 % for the dielectric loss tangent in a wide range of anisotropy and substrate thickness. The problems appear mainly in the SCR; so the split-cylinder resonator can be used neither for big dielectric anisotropy, nor for thick samples – its selectivity becomes considerably smaller compared to the good selectivity of the rest of the resonators. A problem appears also for the measurement of the dielectric loss tangent in very thick samples by CR2 resonator (see Fig. 11*b*).

5. Data for the Anisotropy of Same Popular Dielectric Substrates

5.1 Isotropic material test

A natural test for the two-resonator method and the proposed equivalent 3D models is the determination of the *dielectric isotropy* of clearly expressed isotropic materials ("isotropic-sample" test). Results for for three types of isotropic materials have been presented in Table 3 with increased values of dielectric constant and loss tangent – PTFE, polyolefine and polycarbonate (averaged for 5 samples). The measured "anisotropy" by the pair of resonators CR1/CR2 is very small (< 0.6 % for the dielectric constant and < 4% for the loss tangent) – i. e. the practical isotropy of these materials is obvious. The next "isotropic-sample" test is for polycarbonate samples with increased thickness (from 0.5 to 3 mm) – Fig. 12. The both resonators give close values for the dielectric constant (measured average value ε'_r ~2.6525) even for thick samples, nevertheless that the "anisotropy" ΔA_ε reaches to the value ~2.5 %. The results for the loss tangent are similar – the models give average $\tan\delta_\varepsilon \cong$ 0.005-0.0055 and mean "anisotropy" $\Delta A_{\tan\delta\varepsilon}$ < 4%. All these differences correspond to the practical isotropy of the considered material, especially for small thickness h < 1.5 mm. The final test is for one sample – 0.51-mm thick transparent polycarbonate Lexan® D-sheet ($\varepsilon_r \cong$ 2.9; $\tan\delta_\varepsilon \cong 0.0065$ at 1 MHz), measured by different resonators in wide frequency range 2-18 GHz. The measured "anisotropy" of this material is less than 3 % for ΔA_ε and less than 11 % for $\Delta A_{\tan\delta\varepsilon}$. These values should be considered as an expression of the limited ability of the two-resonator method to detect an ideal isotropy, as well as a possible small anisotropy of microwave materials with relatively small thickness (h < 2 mm).

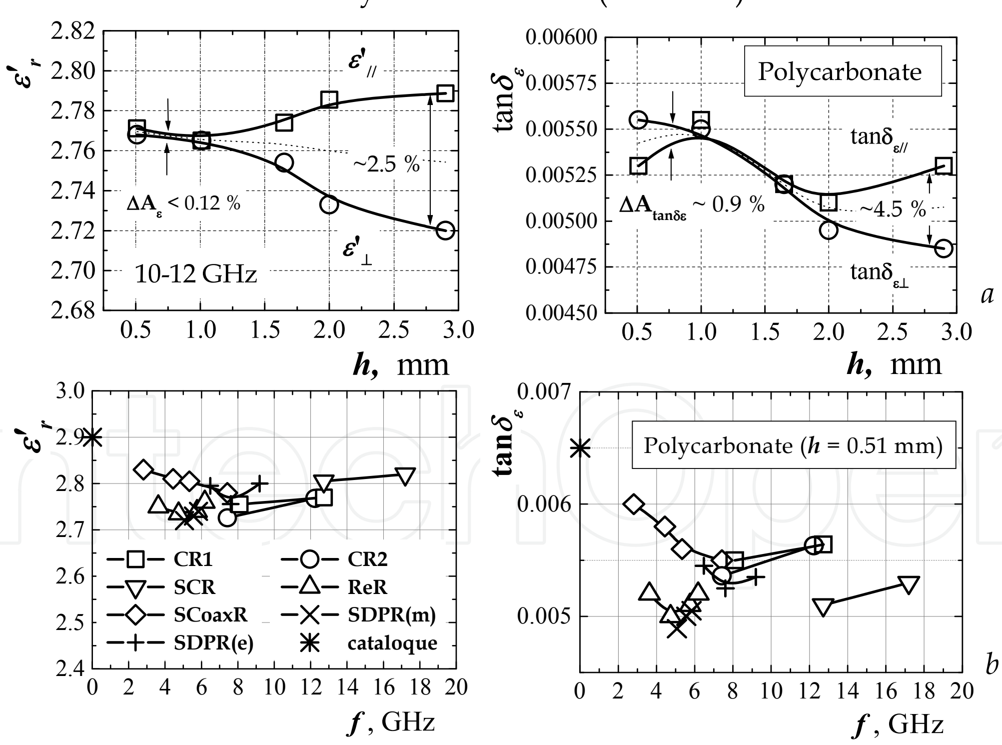

Fig. 12. Isotropy test for polycarbonate sheets: *a*) v/s the thickness *h*; *b*) v/s the frequency

Isotropic Sample	h, mm	CR1: $f_{\varepsilon 1}$, GHz/$Q_{\varepsilon 1}$	$\varepsilon'_{\vert\vert}/\tan\delta_{\varepsilon\vert\vert}$	CR2: $f_{\varepsilon 2}$, GHz/$Q_{\varepsilon 2}$	$\varepsilon'_{\perp}$ / $\tan\delta_{\varepsilon\perp}$	"Anisotropy" $\Delta A_{\varepsilon}/\Delta A_{\tan\delta\varepsilon}$ %
PTFE	0.945	12.6945/9596	2.0451/0.00025	12.3499/3160	2.0470/0.00026	-0.1 / -4.0
Polyolefine	0.7725	12.5856/8004	2.3060/0.00415	12.3756/3120	2.3210/0.00400	-0.6 / 3.7
Polycarbonate	1.000	12.3222/775	2.7712/0.00530	12.2325/1767	2.7650/0.00551	0.2 / -4.0

Table 3. "Isotropic-sample test" of the pair CR1/CR2. Cavity parameters: CR1: f_{01} = 13.1512 GHz; Q_{01} = 14154; D_{eq1} = 30.088 mm; σ_{eq1} = 1.71× 10^7 S/m; CR2: f_{02} = 12.6394 GHz; Q_{02} = 3465; D_{eq2} = 18.156 mm; σ_{eq2} = 0.89× 10^7 S/m

5.2 Data for some popular PWB substrates

The first example for anisotropic materials includes data for the measured dielectric parameters of several commercial reinforced substrates with practically equal catalogue parameters. These artificial materials contain different numbers of penetrated layers (depending on the substrate thickness) of woven glass with an appropriate filling and therefore, they may have more or less noticeable anisotropy. In fact, the catalogue data do not include an information about the actual values of ΔA_ε and $\Delta A_{\tan\delta\varepsilon}$.

The measured results are presented in Table 4 for several RF substrates with thickness about 0.51 mm (20 mils) with catalogue dielectric constant ~3.38 and dielectric loss tangent ~0.0025 -0.0030, obtained by IPC TM-650 2.5.5.5 test method at 10 GHz. The substrates are presented with their authentic designations and with their actual thickness h. We compare all the measured resonance parameters (resonance frequency and Q-factor) by the pair CR1/CR2 and the forth dielectric parameters. A separate column in Table 4 contains the important information about the measured anisotropy ΔA_ε and $\Delta A_{\tan\delta\varepsilon}$. The dielectric parameters are averaged for minimum 5 samples, extracted from one substrate panel with controlled producer's origin. The measurement errors are: $(\Delta\varepsilon'/\varepsilon')_{\vert\vert} \cong 0.3\%$; $(\Delta\varepsilon'/\varepsilon')_{\perp} \cong 0.5\%$; $(\Delta\tan\delta_\varepsilon/\tan\delta_\varepsilon)_{\vert\vert} \cong 1.2\%$; $(\Delta\tan\delta_\varepsilon/\tan\delta_\varepsilon)_{\perp} \cong 3\%$; for $(\Delta f_\varepsilon/f_\varepsilon) \cong 0.04\%$; $(\Delta Q_\varepsilon/Q_\varepsilon) \cong 1.5\%$; $(\Delta h/h) \cong 0.5\%$. Nevertheless, that the substrates are offered as similar ones, they demonstrate different measured parameters and anisotropy, which takes places mainly due to the variations in the longitudinal (parallel) values $\varepsilon'_{\vert\vert}$ and $\tan\delta_{\varepsilon\vert\vert}$, obtained by CR1 and not included in the catalogues. The measured transversal (normal) values $\varepsilon'_{\perp}$ and $\tan\delta_{\varepsilon\perp}$, obtained by CR2, differ

Substrate (20mills thick)	h, mm	CR1: $f_{\varepsilon 1}$, GHz/$Q_{\varepsilon 1}$	$\varepsilon'_{\vert\vert}/\tan\delta_{\varepsilon\vert\vert}$	CR2: $f_{\varepsilon 2}$, GHz/$Q_{\varepsilon 2}$	$\varepsilon'_{\perp}$ / $\tan\delta_{\varepsilon\perp}$	ΔA_ε/ $\Delta A_{\tan\delta\varepsilon}$,%	IPC TM 650 2.5.5.5 @ 10 GHz
Rogers Ro4003	0.510	12.5050/1780	3.67/0.0037	12.4235/2834	3.38/0.0028	8.2/27.7	3.38/0.0027
Arlon 25N	0.520	12.5254/1492	3.57/0.0041	12.4243/2671	3.37/0.0033	5.8/21.6	3.38/0.0025
Isola 680	0.525	12.4820/1280	3.71/0.0049	12.4215/1767	3.32/0.0042	11.1/15.4	3.38/0.003
Taconic RF-35	0.512	12.4552/1176	3.90/0.0049	12.4254/2729	3.45/0.0038	12.2/25.3	3.50/0.0033
Neltec NH9338	0.520	12.4062/1171	4.02/0.0051	12.4303/2849	3.14/0.0025	24.6/68.4	3.38/0.0025
GE Getek R54	0.515	12.4544/1163	3.91/0.0050	12.4238/2715	3.50/0.0038	11.1/27.3	3.90/0.0046 by "split-post cavity"

Table 4. Measured dielectric parameters and anisotropy of some commercial substrates, which catalogue parameters are practically equal or very similar

Substrate	h, mm	parallel $\varepsilon'_{\|\|}/\tan\delta_{\varepsilon\|\|}$	perpendicular $\varepsilon'_{\perp}$ / $\tan\delta_{\varepsilon\perp}$	equivalent ε'_{eq} / $\tan\delta_{\varepsilon eq}$	ΔA_{ε}/ $\Delta A_{\tan\delta\varepsilon}$, %	IPC TM 650 2.5.5.5 10 GHz
Rogers Ro3003	0.27	3.00/0.0012	2.97/0.0013	2.99/0.0013	1.0/−8.0	3.00/0.0013
Rogers Ro3203	0.26	3.18/0.0027	2.96/0.0021	3.08/0.0025	7.2/25.0	3.02/0.0016
Neltec NH9300	0.27	3.42/0.0038	2.82/0.0023	3.02/0.0023	19.2/49.2	3.00/0.0023
Arlon DiClad880	0.254	2.32/0.0016	2.15/0.00093	2.24/0.0011	7.6/53.0	2.17/0.0009
Rogers Ro4003	0.52	3.66/0.0037	3.37/0.0029	3.53/0.0031	8.3/24.3	3.38/0.0027
Neltec NH9338	0.51	4.02/0.0051	3.14/0.0025	3.51/0.0032	24.6/68.4	3.38/0.0025
Isola FR 4	0.245	4.38/0.015	3.94/0.019	-	10.6/21.6	4.7/0.01 (1MHz)
Corsa Alumina	0.60	9.65/0.0003	10.35/0.0004	-	-6.8/-29	9.8-10.7
3M Epsilam 10	0.635	11.64/0.0022	9.25/0.0045	-	22.9/-69	~9.8
Rogers TMM 10i	0.635	11.04/0.0019	10.35/0.0035	10.45/0.0023	6.5/- 59	9.80/0.0020
Rogers Ro3010	0.645	11.74/0.0025	10.13/0.0038	-	14.7/-41	10.2/0.0035

Table 5. Measured parallel, perpendicular and equivalent dielectric parameters of substrates

very slightly from the catalogue data by IPC TM-650 2.5.5.5 test method (the shifts fall into the catalogue tolerances). (An exception is the substrate, measured by a "split-post cavity" technique, which gives its longitudinal parameters). In fact, the bigger differences are observed mainly for the longitudinal parameters, measured along to the woven-glass cloths of the reinforced materials. Therefore, the dielectric constant anisotropy ΔA_{ε} of these substrates varies in the interval from 5.8 % up to 25%, while the loss tangent anisotropy $\Delta A_{\tan\delta\varepsilon}$ varies from 15% up to 68 %. All these results for the anisotropy are caused by the specific technologies, used by the manufacturers (see also the additional results in Table 5 for other substrates in the frequency range 11.5-13 GHz). These data show the usefulness of the two-resonator method – it allows detecting of rather fine differences even for substrates, offered in the catalogues as identical.

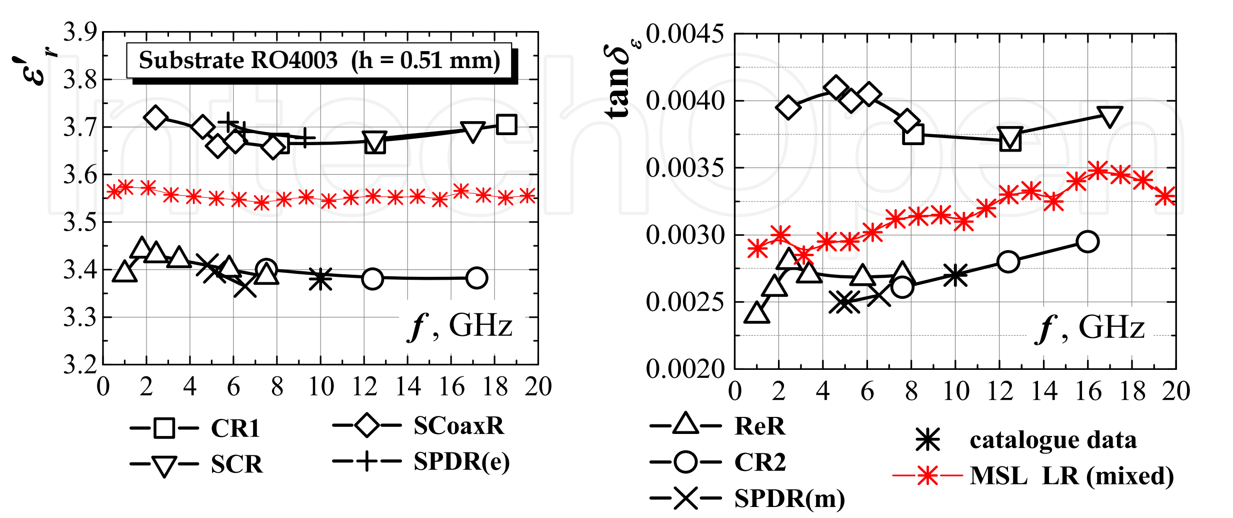

Fig. 13. Measured dielectric parameters ($\varepsilon_{\|\|}$, $\varepsilon_{\perp}$, $\tan\delta_{\varepsilon\|\|}$, $\tan\delta_{\varepsilon\perp}$) of anisotropic substrate Ro4003 by 3 different pairs of resonators and with planar linear MSL resonator

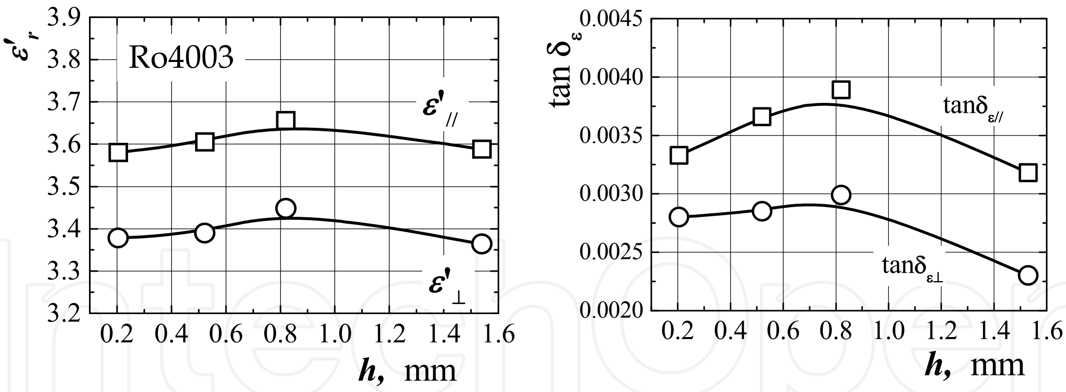

Fig. 14. Dielectric parameters of the anisotropic substrate Ro4003 v/s the thickness

This advantage is demonstrated also in Fig. 13, where the frequency dependencies of the dielectric parameters of one popular microwave non-PTFE reinforced substrate Ro4003 have been presented. The mean measured anisotropy in wide frequency range 2-18 GHz is ~8.7% for ΔA_ε and ~48% for $\Delta A_{\tan\delta\varepsilon}$ (or ~8.4% for ΔA_ε and ~24% for $\Delta A_{\tan\delta\varepsilon}$ at 12 GHz). These data are fully acceptable for design purposes.

5.3 Influence of the substrate thickness and substrate inhomogeneity

The mentioned good selectivity of the two-resonator methods allows also investigating of the dielectric anisotropy of the materials versus their standard thickness, offered in the catalogue. Usually the producers do not specify separate data for different thickness, but this is not enough for substrates with great anisotropy. The data in Fig. 14 are for the considered laminate Ro4003 with a relatively weak anisotropy. Our results show that the average anisotropy of this material does not practically change for the offered thickness values, ΔA_ε ~ 6–8 %, $\Delta A_{\tan\delta\varepsilon}$ ~ 20–26 %. A maximum for the dielectric constant and the loss tangent is observed for a medium thickness, for which this material has probably biggest density. The explanation is that the thinner samples have smaller number of reinforced cloths, while the thicker samples probably contain more air-filled irregularities between the fibers of the woven fabrics. In the both cases the dielectric parameters slightly decrease.

The users, who are permanently working with great volumes of substrates, often have doubts, whether the parameters of the newly delivered sheets are kept in the frame of the catalogue data, or whether they are equal in the different areas of the whole large-size sheets. We have investigated the local inhomogeneity of the main microstrip parameters of a great number of samples extracted from big sheets of two different substrates and the results for the values of their standard deviations (SD's) in % are presented in Table 6. We can see that the SD's of the dielectric constant and the loss tangent of the 2nd substrate are about twice greater than the corresponding values of the 1st substrate. This fact could be connected with the bigger deviation of the substrate thickness SD*h* of the substrate 2. The same effect is also the most likely explanation for the bigger SD's of the perpendicular dielectric parameters of the both substrates compared with the SD's of their parallel dielectric parameters.

Substrate	SD$\varepsilon_{\|\|}$	SD$\varepsilon_{\perp}$	SD $\tan\delta_{\varepsilon\|\|}$	SD $\tan\delta_{\varepsilon\perp}$	SDh	Samples	SDZc	SDε_{eff}	SDβ	SDα
Substrate 1	± 0.2	± 0.5	± 2.0	± 9.0	± 0.2	32	± 0.22	± 0.45	± 0.23	± 4.4
Substrate 2	± 0.80	± 1.00	± 8.5	± 13.0	± 0.7	90	± 0.52	± 0.91	± 0.45	± 6.1

Table 6. Measured standard deviations (in %) of the parameters of large-size substrate sheets

The influence of the measured statistical behaviour of the dielectric parameters over the microstrip impedance Z_c deviations (in Ohms) or over the attenuation α deviations (in dB/cm) is not so big. In fact, the problems appear for the standard deviations of the effective dielectric constant ε_{eff} and the phase shift β (in deg/cm). Nevertheless, that SD's for the 2nd substrate are not so big, SD$\varepsilon_{eff} \cong \pm$ 0.91 % and SD$\beta \cong \pm$ 0.45 %, the total phase delay in relatively long feed lines in big antennas (for example > 10λ_g) can accumulate an additional random phase delay, which can be taken into account in the antenna-array design. For example, two microstrip feeds with equal length 35-40 cm (electrical length 7000-8000 deg) can accumulate a random phase difference about ±30-35 deg, which can easy destroy the beamforming of any planar antenna array.

6. Equivalent Dielectric Constant of the Anisotropic Materials

6.1 Concept of the equivalent dielectric parameters

Is the dielectric anisotropy of the modern RF substrates a bad or a useful property is a discussible problem. In fact, the application of the anisotropy into the modern simulators is not jet enough popular among the RF designers, despite of the proven fact that the influence of this property might be noticeable in many microwave structures (see Drake et. al., 2000). Some examples for utilization of the anisotropic substrates into the modern simulators have been considered by (Dankov et al., 2003). An interesting example for the benefit of taking into account of the substrate anisotropy in the simulator-based design of ceramic filters has been discussed by (Rautio, 2008). The simulation of 3D structures with anisotropic materials is not an easy task, even impossible in some types of simulators (e.g. method-of-moment based MoM simulators, ordinary schematic simulators, etc.). In the finite-element based FEM or FDTD simulators (HFSS, CST microwave studio, etc.) the introduction of the material isotropy is possible (for example in the eigen-mode option), but the older versions of these products do not allow simultaneously simulations of anisotropic and lossy materials. The latest versions, where the simulations with arbitrary anisotropic materials are possible, have special requirements for the quality of the meshing of the structure 3D model. The utilization of the anisotropy in the simulators should be overcome, if *equivalent dielectric parameters* have been introduced, which transforms the real anisotropic planar structure into an equivalent isotropic one. The concept for the equivalent dielectric constant ε_{eq} has been introduced by Ivanov & Peshlov 2003, then the similar concept for the equivalent dielectric loss tangent $\tan\delta_{\varepsilon,eq}$ has been added by Dankov et al., 2003. We can consider ε_{eq} and $\tan\delta_{\varepsilon,eq}$ as resultant scalar parameters, caused by the influence of the arbitrary mixing of longitudinal and transversal electric fields in a given planar structure. Therefore, the constituent isotropic material should be characterized by the following equivalent parameters:

$$\varepsilon'_{eq} = a\,\varepsilon'_{||} + b\,\varepsilon'_{\perp}, \qquad \tan\delta_{\varepsilon eq} = c\,\tan\delta_{\varepsilon||} + d\,\tan\delta_{\varepsilon\perp} \quad . \tag{6}$$

It is easy to predict, that the values of the equivalent dielectric parameters should be dependent on the type of the planar structure under interest. Thus, the usefulness of the equivalent parameters depends on the designed device and it is restricted to transmission lines with non-TEM propagation modes (e. g., coplanar waveguides and coplanar lines), multi-impedance structures and other RF components, which support high-order modes.

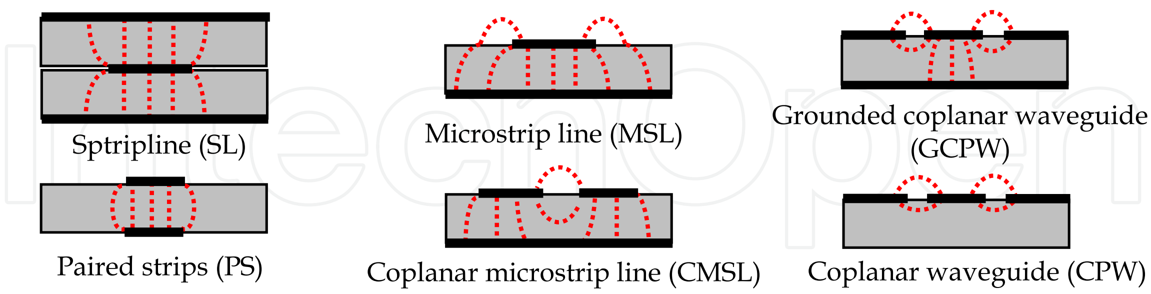

Fig. 15. Investigated planar structures on one substrate – see the results in Fig. 16

6.2 Determination of the equivalent dielectric parameters of different planar lines

In this section we will consider the methods for determination of the equivalent parameters ε_{eq} and $\tan\delta_{\varepsilon eq}$. The investigated structures are schematically shown in Fig. 15. The most usable is the ordinary microstrip line, but the other lines also have applications in many RF projects. Considering the E-field curves of the dominant mode in each structure, we can conclude that the substrate anisotropy may disturb the characteristics of these planar lines with different degree. Let's accomplish an experiment – to measure the effective dielectric constant ε_{eff} and the attenuation α of the considered structures and then to recalculate the actual (in our case: equivalent) dielectric parameters ε_{eq} and $\tan\delta_{\varepsilon eq}$.

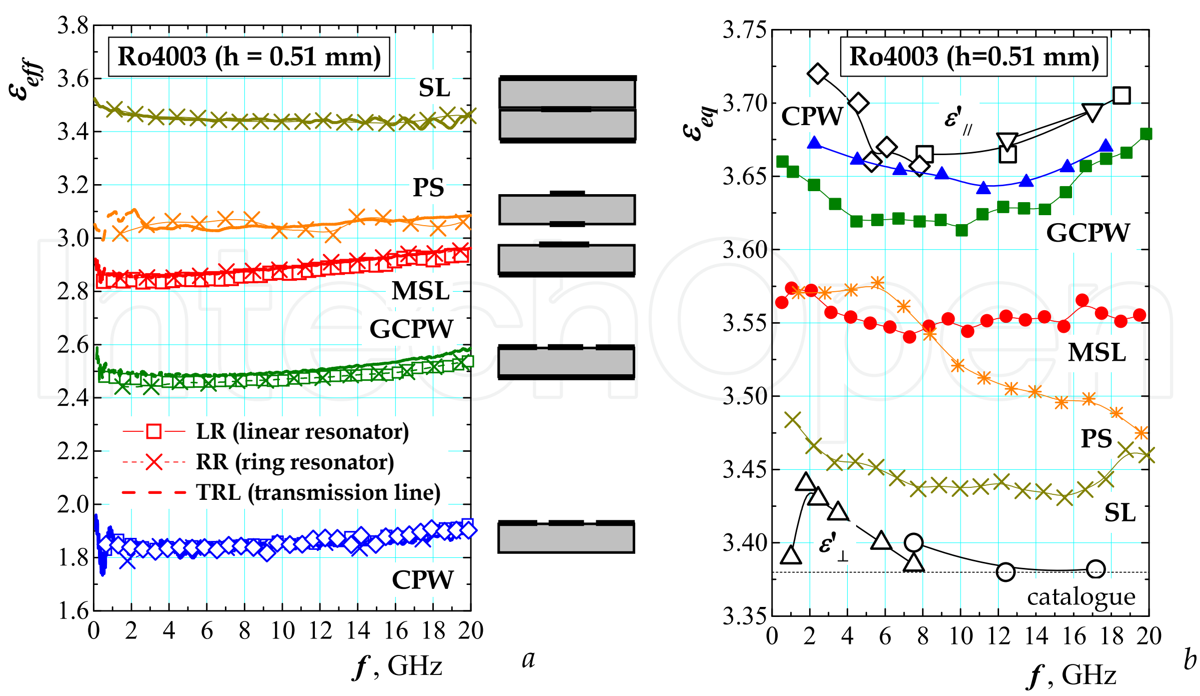

Fig. 16. Unique drawing: the frequency dependencies of the effective (*a*) and equivalent (*b*) dielectric constants of several planar structures fabricated on Ro4003 substrate (0.51 mm)

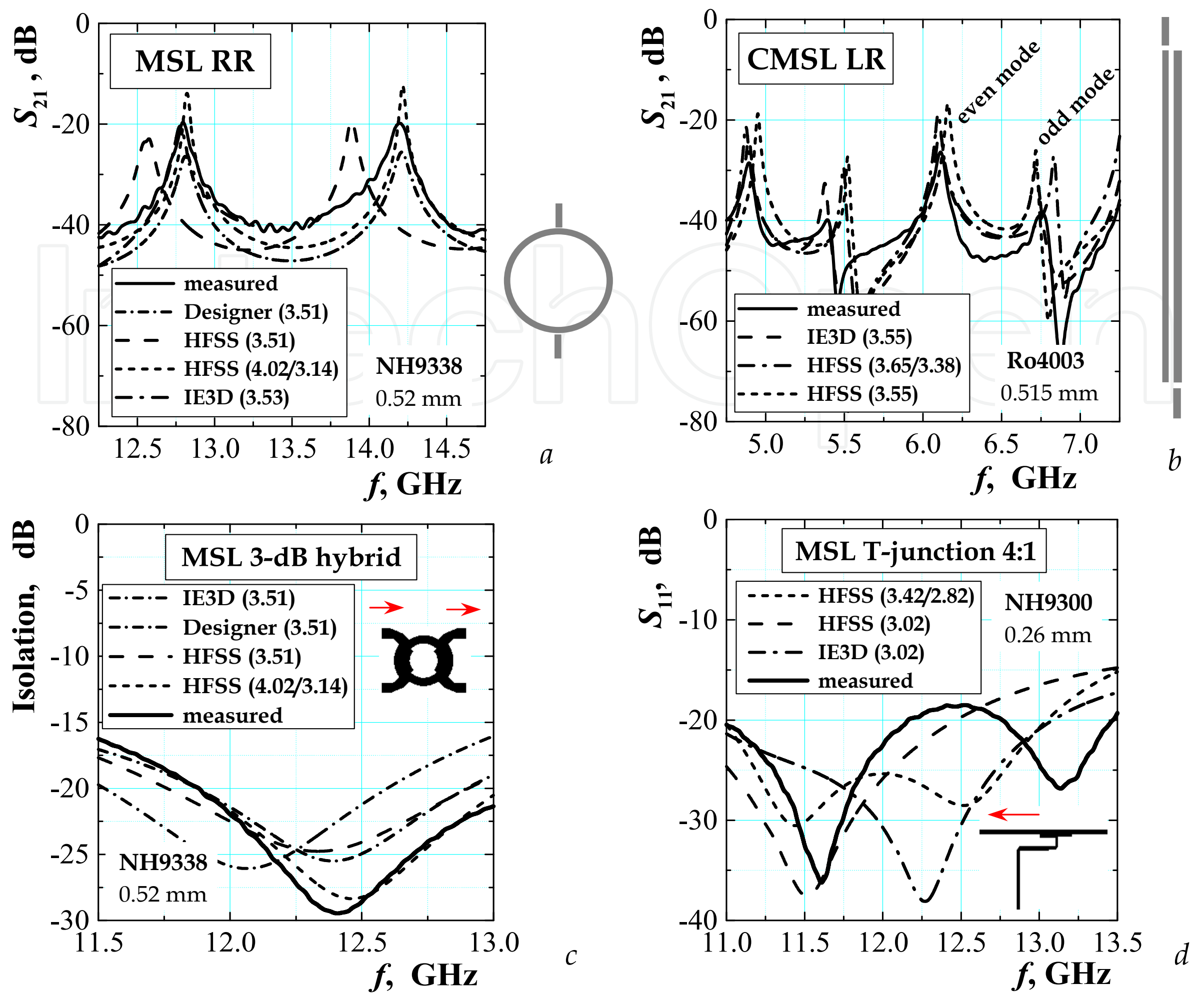

Fig. 17. RF components simulated with anisotropic substrates: *a*) MSL RR (ring diameter 40 mm); *b*) CMSL LR (length 69.6 mm); *c*) 3-dB hybrid; *d*) non-symmetrical T-junction 4:1

The parameters ε_{eff} and α (in dB/cm) can be measured by three independent well-known wide-band methods – the ring and linear resonator method (RR, LR) and the transmission-line method (TRL; the "long & short"-line method) (see Chen et. al., 2004). The results for ε_{eff} are presented in Fig. 16*a* for 5 planar lines printed on one substrate Ro4003 (data for α are not given here). We can see the full coincidence between the used 2 or 3 methods for determination of ε_{eff} -dependencies of each structure. Using the standard methods for converting the parameters: $\varepsilon_{eff} \leftrightarrow \varepsilon_{eq}$; $\alpha \leftrightarrow \tan\delta_{\varepsilon eq}$ (analytical formulas in Wadell, 1991; or standard TRL calculators, which are popular among the RF designers), we can obtain the corresponding equivalent parameters of each planar line (the used method has not been specified, because the presented results are illustrative). The obtained frequency dependencies for ε_{eq} in wide frequency range 1-20 GHz are drown in Fig. 16*b* for each planar line (data for $\tan\delta_{\varepsilon eq}$ are presented in Fig. 13 for micro-strip line only). The dependencies are unique; they show how the value of ε_{eq} is formed for each planar line between the measured values $\varepsilon'_{||}$ and $\varepsilon'_{\perp}$ of Ro4003, depending on the dominant portion of the parallel or perpendicular E fields of the low-order propagation mode. This is also clear evidence why simulations of the planar structures using equivalent parameters are so difficult. In fact, each equivalent parameter depends on the simulated structure and this approach is the most usable mainly for microstrip lines. Fig. 17 gives 4 illustrative examples for simulations of different planar passive devices with equivalent or with anisotropic parameters. The approach with equivalent parameters gives acceptable results for single-mode, resonance and multi-impedance structures (Fig. 17 *a*, *c*), while in the case of multi-mode and multi-impedance non-resonance junctions the simulation results with equivalent parameters do not fit the measured characteristics – Fig. 17 *b* (odd mode), *d*.

7. Conclusion

The importance of the dielectric anisotropy of the modern RF substrates is the main focus of the investigations in this chapter. There are two main reasons to want to have information for the actual anisotropy of a given substrate – to control the technology (necessary for the manufacturers) and to conduct more realistic simulations of the structures, containing anisotropic materials (necessary for the users). The presented investigations show that the two-resonator method is fully acceptable for determination of the substrate dielectric anisotropy by the help of 3D simulators. The achieved measurement error is less than 3 % for the dielectric constant anisotropy and less than 10 % for the dielectric loss tangent anisotropy in wide frequency range by different pairs of measurement resonators (cylinders, split, coaxial and reentrant cylinders and split-post dielectric resonators) separately for the parallel and for the perpendicular parameters. These parameters can be used in the 3D simulators, when structures with anisotropic materials should be simulated.

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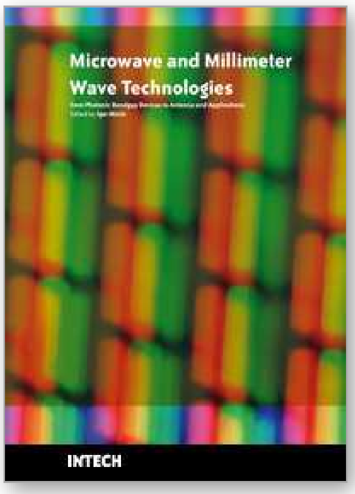

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